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A combined thermodynamic cycle based on methanol dissociation for IC (internal combustion) engine exhaust heat recovery

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ABSTRACT

In this paper, a novel approach for exhaust heat recovery was proposed to improve IC (internal combustion) engine fuel efficiency and also to achieve the goal for direct usage of methanol as IC engine fuel. An open organic Rankine cycle system using methanol as working medium is coupled to IC engine exhaust pipe for exhaust heat recovery. In the bottom cycle, the working medium first undergoes dissociation and expansion processes, and is then directed back to IC engine as fuel. As the external bottom cycle and the IC engine main cycle are combined together, this scheme forms a combined thermodynamic cycle. Then, this concept was applied to a turbocharged engine, and the corresponding simulation models were built for both of the external bottom cycle and the IC engine main cycle. On this basis, the energy saving potential of this combined cycle was estimated by parametric analyses. Compared to the methanol vapor engine, IC engine in-cylinder efficiency has an increase of 1.4–2.1 percentage points under full load conditions, while the external bottom cycle can increase the fuel efficiency by 3.9–5.2 percentage points at the working pressure of 30 bar. The maximum improvement to the IC engine global fuel efficiency reaches 6.8 percentage points.

1. Introduction

Nowadays, energy crisis and environmental pollution have become two primary problems which are concerned by the countries all over the world. As one of the largest consumers of oil and also the largest pollutant emission sources, IC (internal combustion) engine becomes an important object for energy saving and emission reduction [1]. International research trend of IC engine technologies indicates that, at present, scientists mainly focus on the following two aspects for the purpose of relieving energy crisis and reducing pollution gases: one is the research on IC engine alternative fuels owing to the shortage of petroleum resources and the soaring oil prices; the other is to explore new technologies for IC engine energy saving, including the technologies for IC engine waste heat recovery (WHR).

On one hand, alternative fuels are effective means to ease the energy crisis in the word [2,3]. It is generally appreciated that methanol is one of the most common alternative fuels for IC engine. Because of its many advantages, such as widely spread resources, low cost and low soot emissions, methanol has become a research hotspot in the field of IC engine alternative fuels, and is considered to have broad application prospects [4,5]. However, due to its high latent heat of vaporization, methanol is not an ideal fuel for direct application on IC engine. In fact, now methanol is mainly used as a blended fuel, such as methanol gasoline.

On the other hand, waste heat recovery, especially the exhaust heat recovery (EHR), is a useful method to improve the energy utilization efficiency of IC engine [6–8]. In previous research, several kinds of bottom cycles, including six-stroke IC engine cycle with water injection [9], Brayton air cycle [10], steam turbocharging [11] and organic Rankine cycle [12–14], were proposed for IC engine exhaust heat recovery. Conklin JC et al. [9] proposed a concept of highly efficient six-stroke IC engine cycle with water injection for in-cylinder exhaust heat recovery, and they demonstrated the potential to significantly increase the engine's fuel economy. Srinivasan KK et al. [15] analyzed the exhaust heat recovery potential from a dual fuel low temperature combustion engine using an organic Rankine cycle, and they found that fuel conversion efficiency could be improved by an average of 7 percentage points for all injection timings and loads with hot EGR (exhaust gas recirculation) and ORC (organic Rankine cycle) turbocompounding. Roy JP et al. [16] conducted a parametric optimization and performance

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analysis on a waste heat recovery system using organic Rankine cycle. In their studies, R-12, R-123 and R-134a were used as the working fluids of organic Rankine cycle and the cycle performances were compared, and the results show that the organic Rankine cycle using R-123 as working fluid appears to be a choice system for low-grade heat recovery. All the bottom cycles mentioned above can effectively improve the fuel utilization efficiency of IC engine.

However, in the previous studies, concepts of alternative fuels and exhaust heat recovery were separated from each other. It seems more reasonable and practical to realize the goals of energy saving and emission reduction by integrating those two concepts. Besides, in the prior researches, the bottom cycles of waste heat recovery were usually not related to the IC engine's main cycle. Based on above considerations, in this paper, a novel bottom cycle is proposed which uses methanol as working medium for IC engine exhaust heat recovery. Since the bottom cycle working medium is also used as the IC engine's fuel, the bottom cycle and the IC engine main cycle are coupled, and this constructs a combined thermodynamic cycle. More importantly, the concepts of alternative fuel and exhaust heat recovery are combined through the working medium of methanol. After analyzing the cycle, a parametric study is then conducted for this combined cycle to reveal its potential on exhaust heat recovery as well as for direct application of methanol on IC engine.

2. Combined thermodynamic cycle for IC engine exhaust heat recovery

2.1. Concept of the combined thermodynamic cycle

The conceptual sketch of the proposed combined thermodynamic cycle is given in Fig. 1. As shown, a bottom cycle system is coupled to the IC engine exhaust pipe, which uses IC engine exhaust gas as heat source and takes methanol as working medium. In reality, this bottom cycle system could be modified from the IC engine's fuel supply system, thus it can realize the dual-functionalities of supplying fuel for the IC engine and also recovering its exhaust heat energy. The bottom cycle system consists of methanol tank, pump, catalytic cracker (including evaporator and catalytic cracker), control valve and expander, etc. Referred to Fig. 1, the working processes of this combined thermodynamic cycle are described as follows. Firstly, liquid methanol is compressed to a high pressure in the pump; then, the pressurized liquid methanol is directed into the catalytic cracker, in which it is first evaporated into vapor and then dissociated by heat from the IC engine exhaust gas; next, the dissociated methanol gas (mainly H_2 and CO) is directed into the expander, in which it expands and produces mechanical work; finally, the expanded dissociated methanol gas is injected into the IC engine intake pipe, in which it first mixes with fresh air and then flows into cylinders to complete the in-cylinder thermodynamic cycle. As depicted, this combined thermodynamic cycle includes two parts: one is an external bottom cycle (open organic Rankine cycle) for exhaust heat recovery and the other is an in-cylinder working cycle of the IC engine. In this way, the bottom cycle and the in-cylinder working cycle are coupled together.

2.2. Principles of the combined thermodynamic cycle

Fig. 2 is the H–S diagram of the exhaust heat recovery bottom cycle. Point 1 represents the initial state of liquid methanol at the entry of the pump; process 1–2 shows the pressurizing process of liquid methanol in the pump; process 2–3 shows the evaporation and dissociation process of methanol in the catalytic cracker; process 3–4 shows the expansion process of dissociated methanol gas in the expander. Point 4 represents the thermodynamic state of dissociated methanol gas at the outlet of the expander. This is the state that the dissociated methanol gas is injected into the IC engine intake pipe (the injection pressure is higher than intake gas pressure). Since the specific enthalpy of the dissociated methanol gas is higher than liquid methanol and also methanol vapor, fuel heating value is increased by (h5–h1). As a result, the IC engine can receive double effects from this combined thermodynamic cycle: the bottom cycle output work as of (h3–h4)–(h2–h1) and the increase of fuel heating value, as of (h5–h1).

Similarly, the idealized thermodynamic processes of the IC engine in-cylinder cycle are depicted in Fig. 3. Process 6–7 indicates the compression process of the mixed gases (dissociated methanol gas and intake gas); process 7–8 shows the combustion and heat release process of the mixture; process 8–9 displays the expansion process of the combustion gas. After the expansion process, the combustion gas is pushed out of the cylinders through exhaust valves. Finally, exhaust gas is directed into the turbine and produces expansion work over there, and then it is pushed through the catalytic cracker, where it releases heat through a heat transfer process.

Compared to a traditional Rankine cycle "1–2–3–5–1", this bottom cycle "1–2–3–4" is not a closed one since there is no condensation process 5–1. Therefore, it does not require a condenser. Moreover, all the recovered exhaust gas energy can be used without heat rejection. In this combined thermodynamic cycle, the exhaust gas energy recovered by the working medium methanol has two purposes: part of the recovered energy is converted into the expansion work in the bottom cycle, while the

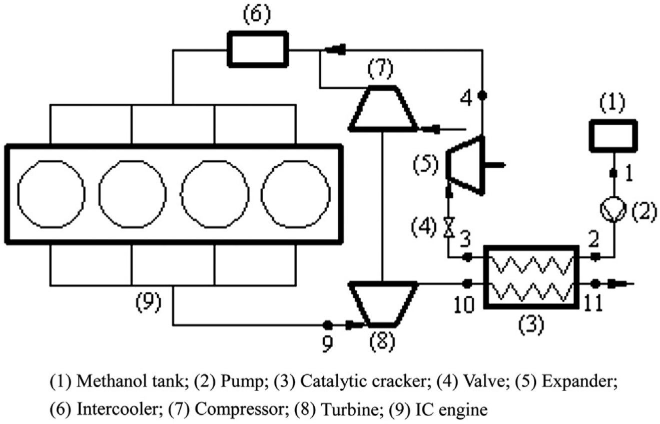


Fig. 1. Schematic diagram of combined thermodynamic cycle for IC engine exhaust heat recovery.

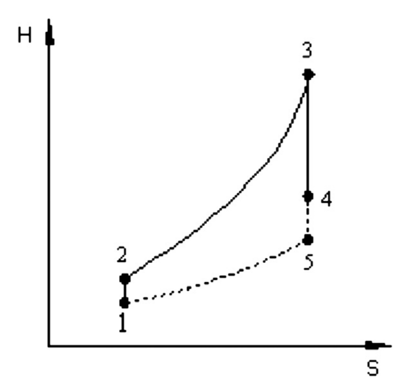


Fig. 2. H–S diagram of exhaust heat recovery bottom cycle.

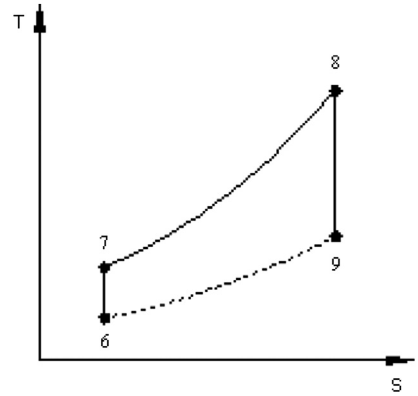


Fig. 3. T–S diagram of IC engine in-cylinder cycle.

remaining is used to evaporate and dissociate methanol to increase its heating value. In this way, the IC engine's fuel utilization efficiency could be enhanced from both the external bottom cycle and the in-cylinder cycle.

2.3. Characteristics of the combined thermodynamic cycle

Then, the characteristics of the combined thermodynamic cycle can be analyzed. Since this combined thermodynamic cycle includes both of the IC engine in-cylinder working cycle and the exhaust heat recovery bottom cycle, it has integrated the advantages of both of them. From the viewpoint of in-cylinder working cycle, the first obvious advantage is that many problems in direct usage of liquid methanol on IC engine can be solved via using methanol vapor or dissociated methanol gas. More importantly, the heating value of the fuel is boosted, which is beneficial for increase of the fuel economy of IC engine. In addition, as the main compositions of dissociated methanol gas are H_2 and CO, the IC engine fueled with dissociated methanol gas will have cleaner combustion and lower emissions since the combustion of hydrogen products zero pollution gases [17,18]. Therefore, if an IC engine is equipped with this combined thermodynamic cycle, not only its in-cylinder fuel efficiency can be increased, but also the harmful emissions can be reduced. Moreover, the goal of on-board production of hydrogen can be realized. From the viewpoint of external bottom cycle, it is a kind of open organic Rankine cycle with higher cycle efficiency but less system component (without condenser). In a word, this combined thermodynamic cycle serves both purposes of recovering exhaust gas energy and improving IC engine fuel heating value. Compared to other bottom cycles of exhaust heat recovery, the system equipment can be reduced, since it could be easily modified from the IC engine fuel supply system.

2.4. Calculation formulas for the combined thermodynamic cycle

Referred to Figs. 2 and 3, the calculation formulas for this combined thermodynamic cycle are given as follows.

1) In the pump, liquid methanol experiences the compression process, and the thermodynamic state of methanol changes from point 1 to 2. During this process, the enthalpy rise of the working medium methanol and the required pump power can be calculated as

$$h_2 = h_1 + \frac{P_{\mathrm{pum}}}{q_{\mathrm{m,m}}} \tag{1}$$

$$P_{\mathrm{pum}} = \frac{p_2 - p_1}{\rho_1} \cdot \frac{q_{\mathrm{m,m}}}{\eta_{\mathrm{pum}}} \tag{2}$$

where, P_{pum} is the required pump power; $q_{\mathrm{m,m}}$ is the mass flow rate of methanol; h_1 and h_2 are the specific enthalpy of methanol at state point 1 and 2, respectively; p_1 and p_2 are the pressure of methanol at the inlet and outlet of the pump, respectively; ρ_1 is the density of methanol at the inlet of the pump; η_{pum} is the isentropic efficiency of the pump.

2) In the catalytic cracker, methanol experiences the evaporation and dissociation processes, and its state changes from liquid state to gaseous state (including dissociated methanol gas). During the evaporation process, the heating value of methanol is increased by approx. 5%. According to the previous research [19], methanol dissociation is a complex chemical process involving many kinds of secondary reactions, but the main reaction equations can be written as

$$CH_3OH(l) \rightarrow CH_3OH(g) \tag{3}$$

$$CH_3OH(g) \rightarrow 2H_2 + CO \tag{4}$$

Since the dissociation rate of methanol usually cannot reach 100%, the IC engine fuel (dissociated methanol gas) consists of H_2, CO and methanol vapor, and the corresponding heating values are given in Table 1. For a complete dissociation process, the heating value of dissociated methanol gas could be increased by about 20% over the liquid methanol.

3) In the expander, the dissociated methanol gas expands from state point 3 to 4. The calculation formula for the expansion power is given as:

$$P_{\mathrm{exp}} = q_{\mathrm{m,m}} \cdot (h_3 - h_4) \cdot \eta_{\mathrm{exp}} \tag{5}$$

And the net output power of the external bottom cycle can be calculated as:

$$P_{\mathrm{net}} = P_{\mathrm{exp}} - P_{\mathrm{pum}} = q_{\mathrm{m,m}} \cdot \left[(h_3 - h_4) \cdot \eta_{\mathrm{exp}} - (h_2 - h_1)/\eta_{\mathrm{pum}} \right] \tag{6}$$

where, P_{exp} is the expansion power of the external bottom cycle; η_{exp} is the isentropic efficiency in the expander; h_4 is the specific enthalpy of the dissociated methanol gas at state point 4; P_{net} is the net output power of the external bottom cycle.

As the main compositions of the dissociated methanol gas are H_2 and CO, both can be treated as ideal gas, Equation (5) can be rewritten as

$$P_{\mathrm{exp}} = q_{\mathrm{m,m}} \cdot c_{\mathrm{P},3} \cdot T_3 \cdot \left(1 - \left(\frac{p_4}{p_3} \right)^{\frac{k-1}{k}} \right) \cdot \eta_{\mathrm{exp}} \tag{7}$$

where, $c_{\mathrm{P},3}$ is the specific heat of the dissociated methanol gas at the expander inlet; T_3 is the corresponding temperature; p_3 and p_4 are the pressure of the dissociated methanol gas at the inlet and outlet

Table 1
Heating values of typical fuel compositions.

Fuel compositions	Heating values	Unit
CH_3OH (l)	19.93	MJ/kg
CH_3OH (g)	21.11	MJ/kg
CO	10.10	MJ/kg
H_2	119.94	MJ/kg

Table 2
Specifications of the IC engine.

Item	Content
Engine type	Inline 4 cylinder
Bore (mm)	66
Stroke (mm)	74
Displacement (l)	1.02
Compression ratio	9.5
Ignition mode	1–3–4–2
Intake mode	Turbocharged

of the expander, respectively; k is the adiabatic expansion exponent of dissociated methanol gas.

4) The air/fuel mixture experiences the combustion and expansion process in the IC engine cylinder. The effective power of the IC engine can be calculated as

$$P_{eng} = \frac{p_{me} \cdot V_s \cdot n \cdot i}{30\tau} \tag{8}$$

where, P_{eng} is the effective power of the IC engine; p_{me} is the BMEP (brake mean effective pressure) of the IC engine; V_s is the displacement of each cylinder; n is the IC engine speed; i is the cylinder number; τ is the stroke number.

And the calculation formula for IC engine in-cylinder efficiency is given as

$$\eta_{eng} = \frac{P_{eng}}{H_u \cdot G_m} \cdot 100\% \tag{9}$$

where, η_{eng} is the in-cylinder efficiency of the IC engine; H_u is the low heating value of liquid methanol; G_m is the consumption rate of methanol.

5) With the combined thermodynamic cycle applied, the global fuel efficiency of the IC engine is defined as

$$\eta_{glo} = \frac{P_{eng} + P_{net}}{H_u \cdot G_m} \cdot 100\% \tag{10}$$

where, η_{glo} is the global fuel efficiency of the IC engine.

In order to better evaluate the energy saving potential of this combined thermodynamic cycle, the improvement to the IC engine global fuel efficiency is defined as

$$\eta_{imp} = \eta_{glo} - \eta_{eng,vap} \tag{11}$$

where, η_{imp} is the improvement to the IC engine global fuel efficiency; $\eta_{eng,vap}$ is the in-cylinder efficiency of the methanol vapor engine, which can be calculated according to Equation (9).

3. Simulation of the combined thermodynamic cycle

3.1. Simulation of the IC engine working cycle

A four cylinder, four stroke, turbocharged, spark ignition engine is used in this study. The specifications of this IC engine are listed in Table 2. Firstly, the corresponding performance simulation model was built based on the simulation software GT-power and calibrated to experimental data, as shown in Fig. 4. In this model, the target boosting pressure of the intake gas was set to 1.5 bar, and the IC engine was fueled with methanol vapor and dissociated methanol gas, respectively. The IC engine fueled with methanol vapor was taken as the basis for comparison. Accordingly, the IC engine fueled with methanol vapor was referred as the methanol vapor engine, and the IC engine fueled with dissociated methanol gas was referred as the dissociated methanol engine. The speed range from 1000 r/min to 5200 r/min was investigated under full load conditions. Through comparing the performances of the dissociated methanol engine and the methanol vapor engine, the effects of the combined thermodynamic cycle on the IC engine in-cylinder working cycle could be acquired. Meanwhile, the performance parameters of the dissociated methanol engine, such as the exhaust gas temperature, exhaust gas mass flow rate, methanol flow rate, etc., were obtained for different speeds, which are used as boundary conditions for designing and calculating the state parameters of the exhaust heat recovery bottom cycle.

3.2. Simulation of the external bottom cycle

According to the calculation formulas given above, the output power of the external bottom cycle depends on various parameters,

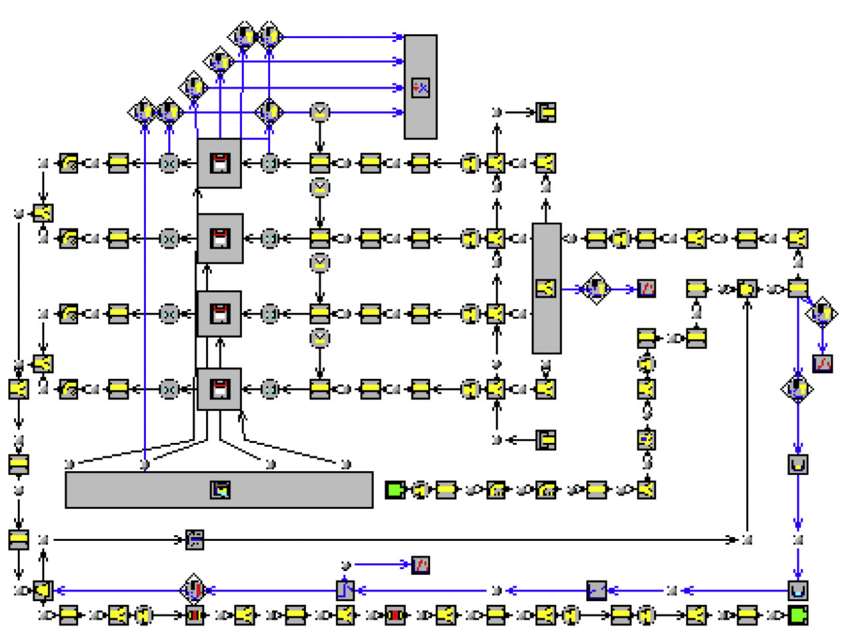


Fig. 4. GT-power simulation model for IC engine working cycle.

Table 3
Design parameters and boundary conditions for the bottom cycle.

Item	Content
Pump efficiency	0.85
Expander efficiency	0.70
Pressure after expansion (bar)	4
Pressure before expansion (bar)	6–30
Expansion ratio range	1.5–7.5
Methanol flow rate range (g/s)	0.96–7.86
IC engine speed range (r/min)	1000–5200
Target boosting pressure (bar)	1.5
IC engine load	Full load

including the mass flow rate of working medium, the pressure and temperature of dissociated methanol gas, etc. Among these parameters, the mass flow rate is determined by the IC engine operating condition, thus it is a parameter known. With a fixed mass flow rate, the methanol gas temperature after dissociation depends on the heating process. Reference [1] indicates that higher working medium temperature contributes to higher cycle efficiency and more output power. However, the maximum temperature of the dissociated methanol gas is constrained by IC engine exhaust gas temperature. Since different IC engine operating condition corresponds to different exhaust gas temperature and fuel mass flow rate, both the maximum temperature of dissociated methanol gas and the mass flow rate of working medium vary accordingly. However, the working pressure of bottom cycle is independent of the IC engine working cycle and can be set as an independent variable. In this study, various bottom cycle working pressure levels, ranging from 6 bar to 30 bar, were investigated so as to analyze their influences on the bottom cycle output power. The design parameters investigated and the parameter variation range for the external bottom cycle are given in Table 3. Among them, the after expansion pressure (at the expander outlet) of the dissociated methanol gas was fixed at 4 bar absolute. In other words, the dissociated methanol gas was injected into the IC engine intake pipe at the pressure of 4 bar. Considering the necessary temperature difference in a heat exchanger, the temperature of the dissociated methanol gas at the catalytic cracker outlet was assumed to be 20 °C lower than the exhaust gas temperature. Similar to the calculation process of the IC engine working cycle, the bottom cycle was calculated for different IC engine speeds under full load. By this means, the output power as well as its percentage in total fuel energy was obtained and the energy saving potential of this bottom cycle could be revealed.

4. Results and discussions

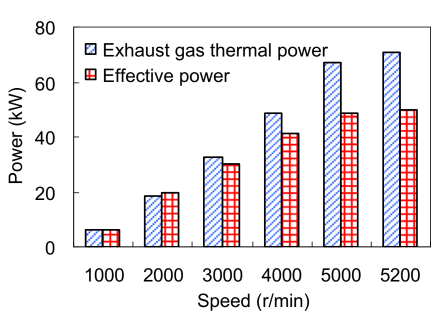
4.1. Exhaust gas energy in the dissociated methanol engine

Since this combined thermodynamic cycle is primarily for IC engine exhaust gas energy recovery, the exhaust gas energy behind the turbine is discussed firstly. Compared in Fig. 5(a) and (b) is the exhaust gas thermal power to the effective power of dissociated methanol engine under full load. Among them, Fig. 5(a) gives the magnitudes of the effective power and the exhaust gas thermal power, while Fig. 5(b) shows their percentages to the total fuel energy. As shown in Fig. 5(a), both the effective power and the exhaust gas thermal power increase with IC engine speed, but the growth rate of exhaust gas thermal power is higher than that of effective power. At the highest speed of 5200 r/min, exhaust gas thermal power comes up to the maximum value of 70.5 kW, which is much higher than the maximum IC engine effective power of 49.7 kW. Although part of exhaust gas energy is used by the exhaust turbine, the remaining is still very high. As can be seen from Fig. 5(b), the percentage of effective work in the dissociated methanol engine first increases and then decreases with the increase of IC engine speed, while the percentage of exhaust gas energy keeps increasing. At low-speed, the percentage of exhaust gas energy is lower than the percentage of effective work. However, the trend changes direction in the medium to high speed. At the highest speed of 5200 r/min, the percentage of exhaust gas energy reaches 45.0%. If this part of energy is recovered, the fuel utilization efficiency of the IC engine could be significantly improved.

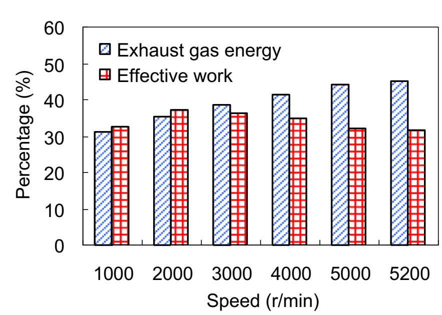
4.2. Working parameters of the combined thermodynamic cycle

Through GT-power modeling, the mass flow rate of methanol required by the IC engine is obtained, as shown in Fig. 6. Actually, the mass flow rate of the methanol fuel is also the mass flow rate of the bottom cycle working medium. Because different IC engine operating condition corresponds to different fuel mass flow rate, the mass flow rate of the bottom cycle working medium can only be adjusted by IC engine working parameters, such as boosting pressure of the intake gas, load (throttle opening) and speed. In this study, the target boosting pressure of the IC engine is fixed at 1.5 bar, and the throttle is kept at the full load condition. As a result, the mass flow rate of the methanol fuel only changes with the IC engine speed. As Fig. 6 illustrates, the mass flow rate of the methanol fuel increases almost linearly with the IC engine speed. At the speed of 1000 r/min, the mass flow rate is only 0.96 g/s. When the IC engine speed increases to 5200 r/min, it comes up to 7.86 g/s. As another key parameter for the combined thermodynamic cycle, the exhaust gas temperature (at the entry of heat recovery system) of the dissociated methanol engine under full load condition is shown in Fig. 7. As can be observed, the exhaust gas temperature increases with IC engine speed as well. When the IC engine speed changes from 1000 r/min to 5200 r/min, the exhaust gas temperature increases from 947.2 K to 1196.2 K.

The exhaust gas temperature (at the entry of heat recovery system) changes over 200 K from low speed to full power and therefore the efficiency of the methanol dissociation process will



(a) Exhaust gas thermal power and effective power



(b) Percentages of exhaust gas energy and effective work

Fig. 5. Exhaust gas energy in the dissociated methanol engine.

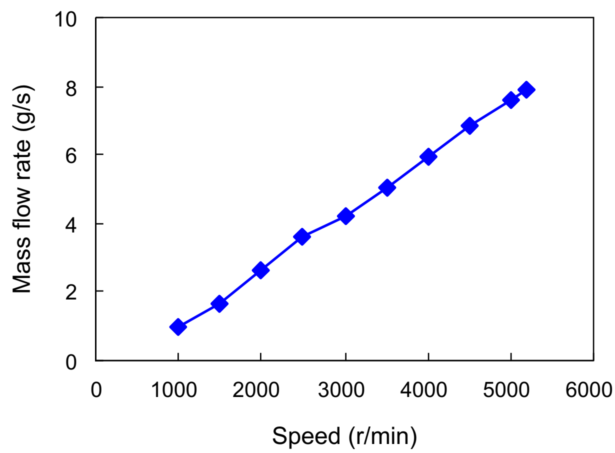


Fig. 6. Mass flow rate of working medium methanol.

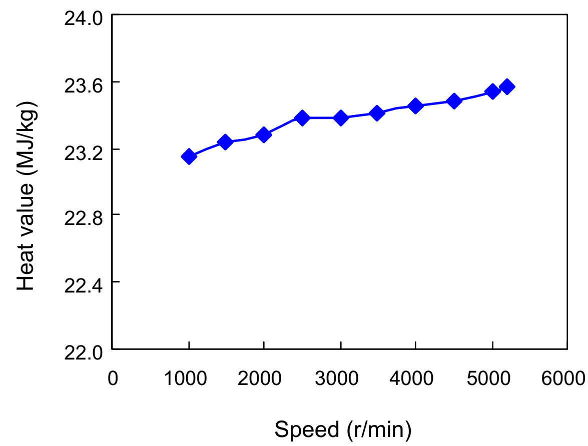


Fig. 8. Fuel heating value vs. IC engine speed.

vary. In this study, the methanol dissociation rate is assumed to be a linear function of the exhaust gas temperature, which is also demonstrated in Fig. 7. According to Equations (3) and (4), the dissociated methanol fuel consists of H_2, CO and methanol vapor, etc., thus the heating value of the dissociated methanol gas changes with the actual composition. Further, the composition depends on the methanol dissociation rate. As a result, the heating value of fuel (dissociated methanol gas) is determined by the methanol dissociation rate. Since the methanol dissociation rate is dominated by the exhaust gas temperature, while the exhaust gas temperature depends on the IC engine speed, in the end, different IC engine speed would correspond to different fuel composition and heating value, as depicted in Fig. 8.

4.3. Energy saving potentials of the combined thermodynamic cycle

What focused on the most in this research is the energy saving potentials of this combined thermodynamic cycle. Firstly, the output power of the external bottom cycle is depicted in Fig. 9. In the predicted output power map shown, the IC engine speed is varied from 1000 r/min to 5200 r/min under full load, and the bottom cycle working pressure is varied between 6 bar and 30 bar. It is clearly shown that the bottom cycle output power increases with both the IC engine speed and the bottom cycle working pressure. The reasons can be listed as follows. On one hand, both the mass flow rate of the methanol fuel and the exhaust gas temperature increase almost linearly with the IC engine speed, as shown in Figs. 6 and 7. The increased exhaust gas temperature contributes to the higher dissociated methanol gas temperature. Furthermore, the increased methanol mass flow rate and the higher dissociated methanol gas temperature result in higher volumetric flow rate through the expander to generate more expansion power. On the other hand, the higher the working pressure is, the larger the pressure expansion ratio (to 4.0 bar exit pressure) will be. As a result, the more enthalpy is extracted out from the dissociated methanol gas to convert into expansion work. As an extreme case, i.e. when the IC engine operates at the highest speed of 5200 r/min and with the highest working pressure of 30 bar, the bottom cycle output power reaches the maximum value of 8.1 kW, which is a 16.3% of power boost for the dissociated methanol engine.

As mentioned above, this combined thermodynamic cycle could improve the fuel utilization efficiency of the IC engine from both the in-cylinder working cycle and the external bottom cycle of exhaust heat recovery. Fig. 10 compares the in-cylinder efficiency between the dissociated methanol engine and the methanol vapor engine under full load conditions. It can be noted that in the speed range studied, the IC engine fueled with dissociated methanol gas has 1.4–2.1 percentage points higher in-cylinder efficiency than the one fueled with methanol vapor. This is due to the higher fuel heating value of the dissociated methanol gas. According to Table 1,

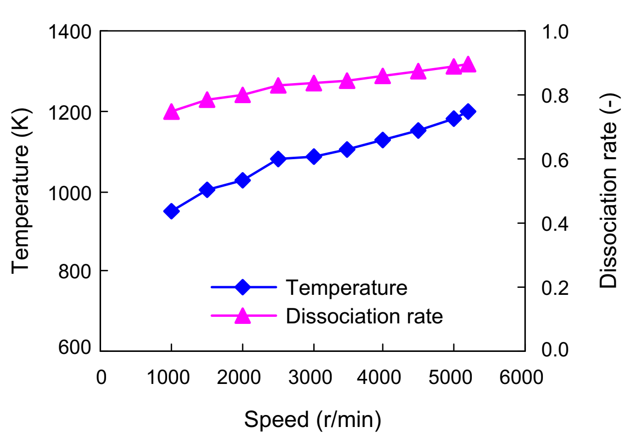


Fig. 7. Exhaust gas temperature and the assumed methanol dissociation rate.

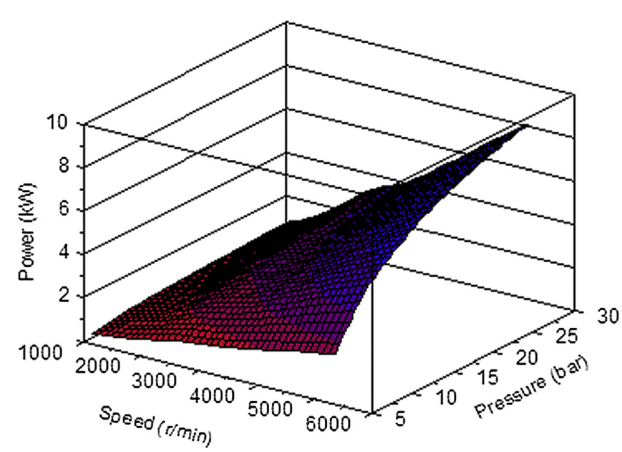


Fig. 9. Output power of the external bottom cycle vs. IC engine speed and working pressure.

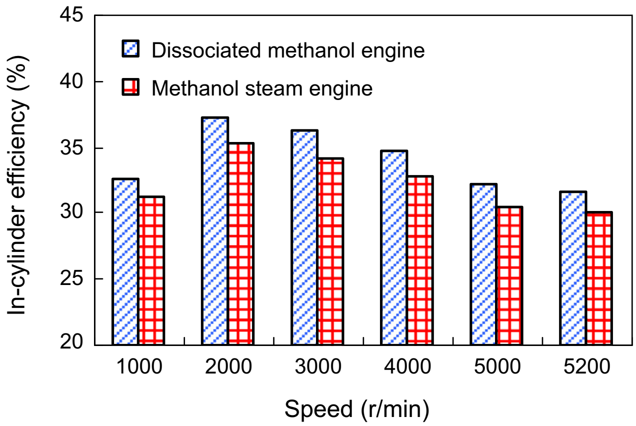


Fig. 10. Comparison of IC engine in-cylinder efficiency.

when methanol is evaporated from liquid state to vapor, its heating value could be increased by approx. 5%. Furthermore, when methanol is dissociated into H_2 and CO, its heating value could be increased by about 20% over the liquid methanol. Nevertheless, the improvement to the IC engine in-cylinder efficiency is very low compared to the improvement to the fuel heating value. The main reason is that the improvement to the IC engine in-cylinder efficiency is restricted by the in-cylinder working process, especially the BMEP [20–22]. As the specific volume of the dissociated methanol gas is much larger than that of the methanol vapor, the BMEP of the dissociated methanol engine drops since the volumetric efficiency is reduced. As a result, part of exhaust gas energy recovered by dissociating methanol fuel is lost during the IC engine in-cylinder cycle. Moreover, any means to improve IC engine in-cylinder efficiency could also enhance the conversion efficiency of the recovered exhaust gas energy from the dissociated methanol fuel. Based on the analyses, a higher intake pressure and/or a higher in-cylinder compression ratio will contribute to a higher conversion efficiency of the recovered exhaust gas energy.

Fig. 11 shows the percentage of the bottom cycle output work in the total fuel energy. In fact, it also indicates the improvement potential of IC engine fuel utilization efficiency by the external bottom cycle. As it shows, the percentage of the bottom cycle output work increases continuously with the increasing of IC engine speed and bottom cycle working pressure. Compared to the IC engine speed, the bottom cycle working pressure plays a more critical role in the bottom cycle output work. For example,

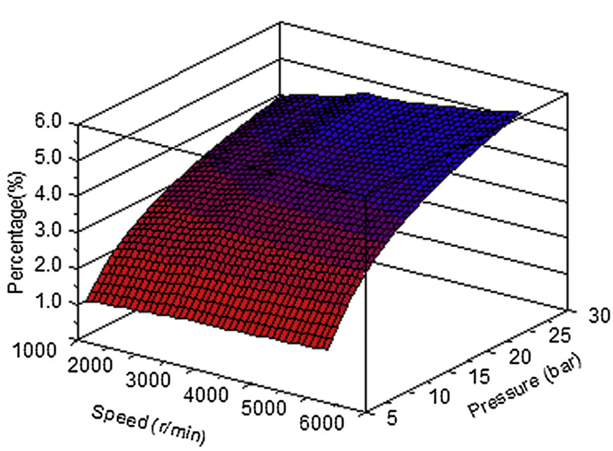


Fig. 11. Percentage of bottom cycle output work in total fuel energy.

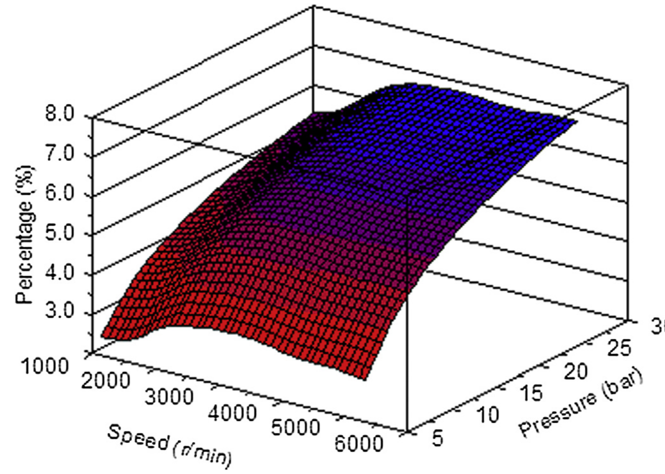


Fig. 12. Improvement to the IC engine global fuel efficiency.

at the fixed bottom cycle working pressure of 30 bar, when the IC engine speed changes from 1000 r/min to 5200 r/min, the percentage of bottom cycle output work in total fuel energy increases from 3.9% to 5.2%. Meanwhile, at the fixed IC engine speed of 5200 r/min, when the bottom cycle working pressure changes from 6 bar to 30 bar, the corresponding percentage increases from 1.3% to 5.2%. The percentage of the bottom cycle output work in the total fuel energy is determined by the pressure and temperature of the dissociated methanol gas, independent of the methanol mass flow rate. The reason for the percentage of the bottom cycle output work increases slowly with the IC engine speed is that the IC engine exhaust gas temperature increase has a slower slope, as shown in Fig. 7, while its rapid increase with the bottom cycle working pressure is due to the linear increase of the pressure expansion ratio over the 4.0 bar after expansion pressure.

Finally, the improvement to the IC engine global fuel efficiency of this combined thermodynamic cycle is discussed, which is depicted in Fig. 12. As proposed, the improvement to the IC engine global fuel efficiency comes from two parts: one is the improvement to the in-cylinder efficiency of the IC engine working cycle, and the other is the percentage of bottom cycle output work in the total fuel energy. As shown in Fig. 12, the improvement to the IC engine global fuel efficiency first increases and then decreases with IC engine speed. This is because the improvement to the IC engine in-cylinder efficiency first increases and then decreases with IC engine speed, as shown in Fig. 10. On the other hand, as the bottom cycle working pressure increases, the improvement to the IC engine global fuel efficiency continues to rise. The reason is that the percentage of the bottom cycle output work monotonically increases with the working pressure. At the speed of 5000 r/min and with the bottom cycle working pressure of 30 bar, the improvement to the IC engine global fuel efficiency comes up to the maximum value of 6.8%. It means that the IC engine global fuel efficiency could be improved by 6.8 percentage points on the basis of methanol vapor engine if this combined thermodynamic cycle is applied. This combined thermodynamic cycle is demonstrated to have great energy saving potential on IC engine.

5. Conclusions

In this paper, a combined thermodynamic cycle using methanol as working medium is proposed for IC engine exhaust heat

recovery. Based on cycle simulation and analysis results, a few conclusions can be drawn as follows:

(1) One of the most significant features of this combined thermodynamic cycle is that the bottom cycle working medium is also used as IC engine fuel. In this way, the bottom cycle of exhaust heat recovery and the in-cylinder working cycle of IC engine are coupled together. In the meantime, the technologies of alternative fuel and exhaust heat recovery are combined on IC engine. In this combined thermodynamic cycle, the in-cylinder working cycle and the external bottom cycle affect each other. On one hand, the maximum temperature of the dissociated methanol gas is limited by the IC engine exhaust gas temperature, and the mass flow rate of the bottom cycle working medium is determined by the IC engine's operating condition. On the other hand, the bottom cycle could boost the IC engine's power output via expansion of the dissociated methanol gas and also promote the IC engine's in-cylinder efficiency by increasing the fuel heating value.
(2) The combined thermodynamic cycle aims to improve IC engine fuel utilization efficiency from both the in-cylinder working cycle and external bottom cycle. Accordingly, the recovered exhaust gas energy serves two purposes. Part of the recovered exhaust gas energy is used to dissociate methanol fuel. By this means, the fuel heating value and then the in-cylinder efficiency could be improved. The rest of the recovered exhaust gas energy is converted into expansion work of the bottom cycle expander. The ultimate energy recovery efficiency of the dissociated methanol fuel is limited by the in-cylinder working cycle, especially the IC engine's thermal-work conversion efficiency. Therefore, increasing the intake pressure and/or in-cylinder compression ratio will result in higher energy recovery efficiency of the dissociated methanol fuel. The energy recovery efficiency of the external bottom cycle depends on the operating temperature and pressure, also higher dissociation temperature and pressure correspond to higher efficiency.
(3) With the combined thermodynamic cycle applied, the IC engine in-cylinder efficiency can be improved by 1.4–2.1 percentage points under full load conditions over the methanol vapor engine. In the meantime, the bottom cycle expansion process could increase the IC engine fuel utilization efficiency by 3.9–5.2 percentage points at the working pressure of 30 bar. As a result, the IC engine global fuel efficiency can be improved by 5.3–6.8 percentage points under full load conditions.
(4) Because the mass flow rate of the bottom cycle working medium is limited by the IC engine operating condition, only part of the exhaust gas energy could be recovered through this combined thermodynamic cycle. In other words, the mass flow rate of the bottom cycle working medium is too low to recover all the exhaust gas energy available, and part of the exhaust gas energy is still wasted. Based on this consideration, a low-temperature organic Rankine cycle system could be added on the exhaust pipe behind the cracker to recover the rest of exhaust gas energy.

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Nomenclature

q_m	mass flow rate [kg/s]
h	specific enthalpy [kJ/kg]
p	pressure [kPa] [MPa]
ρ	density [kg/m^3]
η	efficiency
c_P	specific heat [kJ/(kg K)]
T	temperature [K]
k	adiabatic exponent
P	power [kW]
n	speed [r/min]
i	number of cylinder
τ	number of stroke
V_s	displacement [l]
H_u	low heating value [kJ/kg]
G_m	consumption rate of methanol [kg/s]

Subscripts

pum	pump
exp	expander
eng	engine
me	brake mean effective pressure
glo	global
imp	improvement

Abbreviation

WHR	waste heat recovery
EHR	exhaust heat recovery
EGR	exhaust gas recirculation
ORC	organic Rankine cycle
BMEP	brake mean effective pressure

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